R+D6291-EE-01

Novel Optoelectronic Devices based on combining GaAs and InP on Si

project DAJA45-90-C-0003

Final Technical Report

by P. Demeester

1. Abstract

This work has concentrated on basic technologies for the fabrication of devices which can be used in optical interconnect and optical computing applications.
One of the most important issues is the technology for integration of different devices on the same substrate. Three different possibilities were investigated : heteroepitaxial growth, epitaxial lift-off and patterned epitaxy. The heteroepitaxial technique and the epitaxial lift-off can be used to integrate optoelectronic and electronic devices on the same substrate (resulting in optoelectronic integrated circuits or OEICs). In terms of device performance and material quality, very good results were obtained with the epitaxial lift-off. This was reflected in the realisation of a number of interesting devices and optoelectronic integrated circuits. The heteroepitaxial growth still suffers from the large defect density and although clear improvements were obtained, no good device results could be obtained. As an alternative the bonding by atomic rearrangement was also successfully investigated. The patterned growth technique has a different application field and has important advantages in the fabrication of photonic integrated circuits (PIC) where two (or more) optoelectronic devices are integrated and coupled optically (e.g. laser and waveguide). Much work was devoted to the shadow masked growth technique which has been applied to a number of interesting applications (e.g. multi wavelength laser arrays).

A second important issue is the fabrication of free space optical modulators. These can be used in both optical interconnection and optical computing applications where an essential function is the modulation of the intensity of light propagated in free space. The work was concentrated on the fabrication of InGaAs/AlGaAs multi quantum well modulators on GaAs.
The project was finished succesfully with 43 publications (in which the project was acknowledged) and with 3 PhD degrees (which were considerably supported by the project).

2. Statement of problem

The aim of this project was to investigate some basic technological steps for the fabrication of novel optoelectronic devices for optical interconnection and computing. The basic technologies were split into four major research areas : (1) heteroepitaxial growth, (2) patterned growth, (3) MQW modulators and (4) Epitaxial Lift-Off.

3. Summary of the most important results

In this report we will briefly summarize the most important results obtained during the whole projects. Detailed information can be found in the interim reports and the publications.

3.1 Heteroepitaxial growth

Heteroepitaxial growth is important to combine different materials monolithically on a single substrate. Typical examples are the growth of GaAs on InP or GaAs on Si.

This part has mainly concentrated on the growth of InP on GaAs and InP on GaAs on Si. State of the art material quality was obtained by the use of selective growth and temperature cycling techniques. This work has resulted in a number of publications [3, 11, 12, 18, 21, 22, 26] which deal mainly with the fundamental problems of the growth process (MOVPE based). In the second part of the project we have also investigated the Bonding by Atomic Rearrangement (BAR) technique for InP on GaAs and

InP on Si, as an alternative to direct epitaxial growth. This has resulted in good material quality and low loss InP waveguides on GaAs.

3.2. Patterned growth

Patterned growth is a techniques where epitaxial layers are grown on a patterned substrate in order to change the normal growth behaviour observed during non-patterned growth. This finds interesting applications in photonic integrated circuits, advanced devices etc.

Three different patterning techniques have been investigated : non-planar growth, selective growth and shadow masked growth. Most work has been devoted to the in house developed Shadow Masked Growth (SMG) technique [5, 9, 14, 17, 19, 23, 25, 27, 28, 31, 32, 33, 36, 40, 43,] although good results were also obtained with the two other techniques [2, 28] . Besides the basic characterization, some interesting device results have been obtained (using SMG). These include : multiwavelength laser arrays (wavelength span of 130 nm, both on GaAs and InP), extended cavity lasers, lasers with tapered facets resulting in more symmetric farfield, tapered waveguides with improved coupling to fibres, broad spectrum LEDs. A number of the above mentioned papers were invited papers [19, 25, 36, 43].

3.3. MQW modulators

The use of free space optical modulators opens interesting perspectives for optical interconnection and computing. One of the important problems is the fabrication of high quality modulators on transparant substrates.

This work has concentrated on the developement of InGaAs/AlGaAs MQW structures for optical modulators (both transmission and reflection). Very good material quality was obtained resulting in good device results (e.g. Asymmetric Fabry-Perot Modulators). Different publications resulted from the research on modulators [6, 8, 16, 20, 24, 29, 30].

3.4. Epitaxial Lift-Off (ELO)

An interesting alternative to the heteroepitaxial growth is the transplantation of epitaxial films (as developed by Bellcore in 1987). This technique has the advantage that the layers can be grown lattice matched without introducing defects (as is the case with heteroepitaxial growth). It also allows the combination of GaAs with other materials (glass, $LiNbO_3$)

The basic technology for epitaxial lift-off has been developed to a stage where good device results can be obtained. One of the major break throughs was the use of under water transplantation, which reduced the defect density by two orders of magnitude! Numerous device results were obtained : GaAs LEDs and lasers on Si, GaAs MESFETs on Si and InP, GaAs optical modulator on glass, optoelectronic integrated circuits (GaAs-LED + GaAs-FET , GaAs FET + $LiNbO_3$ switch, etc.). This resulted also in a large number of publications [1, 4, 7, 13, 15, 20, 35, 37, 39, 41, 42] including a number of invited papers [10, 34, 38].

4. List of publications

[1] I. Pollentier, P. Demeester, A. Ackaert, L. Buydens, P. Van Daele, R. Baets; "The epitaxial lift-off of GaAs LEDs to Si for the fabrication of opto-electronic integrated circuits"; Electronics Letters, Vol. 26, Nr. 3, 1 February 1990, pp. 193-194

[2] L. Buydens, P. Demeester, M. Van Ackere, A. Ackaert, P. Van Daele; "Thickness variations during MOVPE growth on patterned substrates"; J. Electronic Materials, Vol. 19, Nr. 4, April 1990, pp. 317-321

[3] A. Ackaert, I. Pollentier, P. Demeester, P. Van Daele, D. Rondi, G. Glastre, A. Enard, R. Blondeau, P. Jarry, J. Le Bris, M. Renaud, H. Angement, A. Carvailles; "GaAs on InP based optoelectronic integrated circuits for optical switching networks"; NATO Advanced Research workshop on Condensed Systems of Low Dimensionality, April 1990, Marmaris, Turkey

[4] I. Pollentier, L. Buydens, A. Ackaert, P. Demeester, P. Van Daele, F. De Pestel, D. Lootens, R. Baets; "Monolithic integration of an InGaAs/GaAs/AlGaAs strained layer SQW LED and GaAs MESFET using epitaxial lift-off"; Electronics Letters, Vol. 26, Nr. 13, 21 June 1990, pp. 925-926

[5] P. Demeester, L. Buydens and P. Van Daele; "Growth velocity variations during metal organic vapor phase epitaxy through an epitaxial shadow mask"; Appl. Phys. Letters, Vol. 57, Nr. 2, 9 July 1990, pp. 168-170

[6] L. Buydens, P. Demeester, P. De Dobbelaere, P. Van Daele; "InGaAs/AlGaAs vertical optical modulators and sources on a transparent GaAs substrate"; Meeting on Future Directions for Optics in Computers, Editor : Laboratoire d'Optique P.M. Duffieux - URA CNRS 214 Universite de Franche-Comte - Besancon, 17-18 July 1990, Besançon, France, pp. 5/5-5/9

[7] I. Pollentier, A. Ackaert, P. Demeester, P. Van Daele; "Fabrication of high radiance LEDs by epitaxial lift-off"; SPIE's International Conference on Physical Concepts of Materials for Novel Optoelectronic Device Applications, SPIE conference proceedings, Vol. 1361, 28 October - 1 November 1990, Aachen, Germany

[8] L. Buydens, P. Demeester, P. De Dobbelaere, P. Van Daele; "InGaAs/AlGaAs vertical optical modulators and sources on a transparant GaAs substrate"; SPIE's International Conference on Physical Concepts of Materials for Novel Optoelectronic Device Applications, SPIE conference proceedings, Vol. 1361, 28 October - 1 November 1990, Aachen, Germany

[9] P. Demeester, I. Moerman, Y. Zhu, P. Van Daele and J. Thomson; "Shadow masked growth for photonic integrated circuits"; SPIE's International Conference on Physical Concepts of Materials for Novel Optoelectronic Device Applications, SPIE conference proceedings, Vol. 1361, 28 October - 1 November 1990, Aachen, Germany

[10] P. Demeester, I. Pollentier, L. Buydens, P. Van Daele; "Novel optoelectronic devices and integrated circuits using epitaxial lift-off"; SPIE's International Conference on Physical Concepts of Materials for Novel Optoelectronic Device Applications, SPIE conference proceedings, Vol. 1361, 28 October - 1 November 1990, Aachen, Germany

[11] G. Coudenys, I. Moerman, A. Ackaert, P. Demeester, I. Croston, P. De Dobbelaere, M. Van Ackere, P. Van Daele; "Lattice mismatched MOVPE growth of InP and GaAs on masked substrates"; Crystal Properties and Prepation, Editor: E. Lendvay; Trans Tech Publications, ISBN 0-87849-616-5, Vol. 32-34, 1991, pp. 624-629

[12] P. Demeester, A. Ackaert, G. Coudenys, I. Moerman, L. Buydens, I. Pollentier, P. Van Daele; "Relaxed lattice-mismatched growth of III-V semiconductors"; Progress in Crystal Growth and Characterization, Pergamon Press, Vol. 22, Nr. 1-2., 1991, pp. 53-141

[13] I. Pollentier, L. Buydens, P. Van Daele, P. Demeester; "Fabrication of a GaAs/AlGaAs GRIN-SCH SQW laserdiode on silicon by epitaxial lift-off"; IEEE Photonics Technology Letters, Vol. 3, Nr. 2, February 1991, pp. 115-117

[14] P. Demeester, Y. Zhu, I. Moerman, L. Buydens, D. Lootens, K. De Vlaeminck, P. Van Daele and R. Baets; "Lateral bandgap engineering using shadow masked growth"; Integrated Photonics Research Topical Meeting, Optical Society of America, Technical Digest Series, Vol. 8, April 1991, Monterey, USA, pp. 101-102

[15] I. Pollentier, P. Demeester, P. Van Daele, D. Rondi, G. Glastre, A. Enard and R. Blondeau; "Fabrication of long wavelength OEICs using GaAs on InP epitaxial lift-off technology"; Third International Conference on Indium Phosphide and Related Materials, IEEE Catalog #91CH2950-4, April 1991, Cardiff, UK, pp. 268-271

[16] L. Buydens, P. Demeester, M. Van Ackere, P. Van Daele; "InAlGaAs/AlGaAs SSQW GRINSCH lasers for the wavelength region between 800 and 870 nm"; Electronics Letters, Vol. 27, Nr. 8, 11 April 1990, pp. 618-620

[17] P. Demeester, L. Buydens, I. Moerman, D. Lootens, P. Van Daele; "Non-planar MOVPE growth using a novel shadowmasking technique"; J. Crystal Growth, Vol. 107, Nr. 1-4., 1991, pp. 161-165

[18] G. Coudenys, I. Moerman, G. Vermeire, P. Van Daele, P. Demeester; "New techniques to improve the InP/GaAs quality"; 4th European Workshop on MOVPE, 5-7 June 1991, Nijmegen, The Netherlands

[19] P. Demeester, Y. Zhu, G. Coudenys, G. Vermeire, D. Lootens, K. De Vlaemynck, P. Van Daele; "Lateral variations in III/V heterostructures using patterned substrates"; 4th European Workshop on MOVPE, 5-7 June 1991, Nijmegen, The Netherlands

[20] L. Buydens, P. De Dobbelaere, P. Demeester, I. Pollentier, P. Van Daele; "GaAs/AlGaAs MQW vertical optical modulators on glass using the ELO technique"; Optics Letters, Vol. 16, Nr. 12, 15 June 1991, pp. 916-918

[21] G. Coudenys, I. Moerman, P. Demeester; "Influence of the nucleation and anealing conditions on the quality of InP layers grown on GaAs by MOCVD"; J. Crystal Growth, Vol. 114, 1991, pp. 314-320

[22] P. Demeester, G. Coudenys, L. Buydens, A. Ackaert, I. Moerman, I. Pollentier and P. Van Daele; "Recent developments in lattice mismatched and strained layer heterostructures"; Materials Science and Engineering, Vol. B9, 1991, pp. 129-136

[23] G. Vermeire, P. Demeester, K. Haelvoet, B. Van der Cruyssen, G. Coudenys, P. Van Daele; "Broad band side emitting GaAs/AlGaAs/InGaAs single quantum well LED's"; 18th International Symposium on Gallium Arsenide and Related Compounds, Institute of Physics Conference Series, Vol. 120, Nr. 10, 9-12 September 1991, Seattle, USA, pp. 499-504

[24] L. Buydens, P. Demeester, Z. Yu, P. Van Daele; "High-Contrast/Low Voltage Normally On InGaAs/AlGaAs Asymmetric Fabry-Perot Modulator"; IEEE Photonics Technology Letters, Vol. 3, Nr. 12, December 1991, pp. 1104-1106

[25] G. Coudenys, G. Vermeire, Y. Zhu, I. Moerman, L. Buydens, P. Van Daele, P. Demeester; "Novel growth techniques for the fabrication of photonic integrated circuits"; Advanced III-V Compound Semiconductor Growth, Processing and Devices, USA-MRS Fall meeting, MRS Symposium Proceedings, editors: S.J. Pearton, D.K. Sadana, J.M. Zavada, Vol. 240, 2-6 December 1991, Boston, USA, pp. 15-26

[26] I. Pollentier, L. Buydens, P. Demeester, P..Van Daele, A. Enard, E. Lallier, G. Glastre, D. Rondi; "Monolithic integration of GaAs MESFET and InP/InGaAsP 2x2 optical switch"; IEE Electronics Letters, Vol. 27, Nr. 25, 5 December 1991, pp. 2339-2340

[27] K. De Vlamynck, G. Coudenys, P. Demeester; "Comparative analysis of growth rate reductions on shadow masked substrates"; Appl. Phys. Letters, Vol. 59, Nr. 24, 9 December 1991, pp. 3145-3147

[28] G. Coudenys, I. Moerman, W. Vanderbauwhede, P. Van Daele, P. Demeester; "Selective and shadow masked MOVPE growth of InP/InGaAs(P) heterostructures and quantum wells"; J. Crystal growth, Vol. 124, 1992, pp. 497-501

[29] L. Buydens, P. Demeester, P. Van Daele; "Asymmetric Fabry-Perot modulators with an InGaAs/AlGaAs active region"; Optical and Quantum Electronics, Chapman & Hall, Vol. 24, Nr. 2, February 1992, pp. S167-S175

[30] L. Buydens, P. Demeester, Z. Yu, P. Van Daele; "High quality In15Ga85As/AlxGa(1-x)As strained multi quantum wells grown by Metal Organic Vapour Phase Epitaxy"; J. Appl. Phys., Vol. 71, Nr. 7, 1 April 1992, pp. 3249-3255

[31] G. Coudenys, I. Moerman, Y. Zhu, P. Van Daele, P. Demeester; "Lateral bandgap engineering for InP-based Photonic Integrated Circuits"; Fourth International Conference on Indium Phosphide and Related Materials (IPRM-4), IEEE Catalog #: 92CH3104-7, 20-24 April 1992, Newport, Rhode Island, USA, pp. 202-205

[32] G. Vermeire, L. Buydens, P. Van Daele, P. Demeester; "Side-emitting GaAs/AlGaAs SQW LED's showing a wide spectrum using shadow masked growth"; IEE Electronics Letters, Vol. 28, Nr. 10, 7 May 1992, pp. 903-905

[33] G. Coudenys, I. Moerman, Y. Zhu, P. Van Daele, P. Demeester; "Multi-wavelength InGaAs/InGaAsP strained layer MQW laserarray using shadow masked growth"; IEEE Photonics Technology Letters, Vol. 4, Nr. 6, June 1992, pp. 524-526

[34] I. Pollentier, P. Demeester, P. Van Daele; "Epitaxial lift-off: a combination of the advantages of hybrids and monolithic integration"; Tenth Annual European Optical Communications and Networks Conference EFOC/LAN'92, IGI Europe, ISBN 3-905084-06-6, 24-26 June 1992, Paris, France, pp. 66-71

[35] I. Pollentier, P. Demeester, P. Van Daele, L. Martens; "Optimization and reliability of epitaxial lift-off for OEIC fabrication"; LEOS 1992 Summer Topical Meeting Digest on Integrated Optoelectronics, IEEE Catalog #: 92TH0421-8, Library of Congress #: 91-77849, 5-7 August 1992, Santa Barbara, California, USA, pp. 77-78

[36] P. Demeester, G. Coudenys, G. Vermeire, I. Moerman,Y. Zhu, L. Buydens, C. Eeckhout, P. Van Daele; "Shadow masked growth and its applications"; Sources and detectors for fiber communications, Edt. Stephen D. Hersee, ISBN 0-8194-0967-7, Library of Congress No 92-62407, SPIE conference proceedings (1993), Vol. 1788, 8-9 September 1992, Boston, USA, pp. 55-70

[37] I. Pollentier, L. Buydens, P. Van Daele, P. Demeester; "Heteroepitaxial or epitaxial lift-off approach for future optoelectronic GaAs MESFET/InP optical switch integration ?"; Microelectronic Engineering (ESSDERC'92), Editor: H.E. Maes, R.P. Mertens, R.J. Van Overstraeten; Elsevier Science Publishers, ISBN 0-444-89478-0, Vol. 19, 14-17 September 1992, Leuven, Belgium, pp. 207-210

[38] P. Demeester, I. Pollentier, P. De Dobbelaere, C. Brys, P. Van Daele; "Epitaxial lift-off and its applications"; Semiconductor Science and Technology, Institute of Physics Publishing, Vol. 8, 1993, pp. 1124-1135

[39] I. Pollentier, C. Brys, P. Demeester, P. Van Daele, L. Martens; "Transplantation of epitaxially lifted-off MESFET's fabricated by a commercial foundry : operation and reliability"; Electronics Letters, Vol. 29, Nr. 3, 4 February 1993, pp. 291-293

[40] I. Moerman, G. Coudenys, G. Vermeire, P. Van Daele, P. Demeester; "Atmospheric and low pressure Shadow Masked MOVPE growth of InP/InGaAs(P) and InGaAs/(Al)GaAs heterostructures and quantum wells"; Sixth biennial workshop on Organometallic Vapor Phase Epitaxy, The Minerals, Metals & Materials Society (TMS), 21-25 March 1993, Palm Springs, California, USA

[41] C. Brys, I. Pollentier, J.-L. Peyre, P. Jarry, M. Renaud, T. Morf, P. De Dobbelaere, P. Demeester, P. Van Daele, T. Martinson; "Epitaxial lift-off integration of GaAs receiver amplifier with InGaAs waveguide fed photodetectors"; European Conference on Integrated Optics (ECIO'93), editor: Patrick Roth, CSEM, 18-22 April 1993, Neuchatel, Switzerland, pp. 2/28-2/29

[42] I. Pollentier, C. Brys, P. Debie, R. Coppoolse, L. Martens, J. Vandewege, P. Van Daele, P. Demeester; "Epitaxially lifted-off GaAs MESFET's on InP for optoelectronic integration"; Fifth International Conference on Indium Phosphide and Related Materials (IPRM-5), IEEE Catalog #93CH3276-3, Library of Congress #93-77243, 19-22 April 1993, Paris, France, pp. 365-368

[43] G. Vermeire, G. Coudenys, I. Moerman, Y. Zhu, L. Buydens, C. Eeckhout, P. Van Daele, P. Demeester; "Photonic integration using shadow masked growth"; accepted for publication in Proceedings of the 17h State-of-the-art Program on Compound Semiconductors (SOTAPOCS XVII), Electronics and Dielectric Science and Technology Divisions of The Electrochemical Society, 12-16 October 1992, Toronto, Canada

5. Participation of scientific personnel

P. Demeester as group leader

I. Pollentier was involved in the ELO work and he received a PhD degree in 1993

G. Coudenys was involved in the heteroepitaxial growth and the SMG and he received a PhD degree in 1993

L. Buydens was involved in the modulator work and he received a PhD degree in 1993

Gent, nov. 1993